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DIRECT USE OF COAL IN A FUEL CELL: FEASIBILITY INVESTIGATION

Robert D. Weaver, et al

Stanford Research Institute

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DIRECT USE OF COAL IN A FUEL CELL: FEASIBILITY INVESTIGATION

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16. ABSTRACT The report gives results of the first phase of a study of the feasibility of using coal to produce electricity directly in a fuel cell that uses a molten-carbonate electrolyte, a coal anode, and an air cathode. The cell voltage, the polarization of the anode, and the nature of the gaseous products formed were investigated. Electrodes made from charred coal yielded open-circuit voltages close to 1 V. At 975 K, the activation plus concentration polarization was about 200 mV at current densities of 100 mA per sq cm and larger. At higher temperatures smaller polarizations were observed. The gaseous anode products were primarily CO_2, with some CO. Current efficiencies were somewhat less than 100 percent. The low values were possibly due to losses of anode gases by mechanical means. Coal ash added to the molten electrolyte did not appear to be deleterious to cell operation. Descriptions of possible future engineering systems and thermodynamic limitations are presented.

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Coal	Air Cathode	21D
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by

R. D. Weaver, Laura Tietz,
and Daniel Cubicciotti

Stanford Research Institute
Menlo Park, California 94025

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ABSTRACT

The first phase of a study of the feasibility of using coal to produce electricity directly in a fuel cell is reported. The cell under investigation is a molten-carbonate electrolyte cell using a coal anode and an air cathode. The cell voltage, the polarization of the anode, and the nature of gaseous products formed were investigated. Electrodes made from charred coal yielded open-circuit voltages close to one volt. At 975 degrees Kelvin, the activation plus concentration polarization was about 200 millivolts at current densities of 100 milliamperes per centimeter square and larger. At higher temperatures smaller polarizations were observed. The gaseous anode products were primarily carbon dioxide, with some carbon monoxide. Current efficiencies were somewhat less than 100 percent. The low values were possibly due to losses of anode gases by mechanical means. Coal ash added to the molten electrolyte did not appear to be deleterious to cell operation. Descriptions of possible future engineering systems and thermodynamic limitations are presented.

This report was submitted in fulfillment of Contract No. 68-02-1808 by Stanford Research Institute under the sponsorship of the Environmental Protection Agency. Work was completed as of 28 February 1975.

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CONTENTS

ABSTRACT iii

LIST OF FIGURES vi

LIST OF TABLES vii

ACKNOWLEDGMENTS viii

I CONCLUSIONS 1

II RECOMMENDATIONS 3

III INTRODUCTION 4

IV EXPERIMENTAL PROCEDURES 12

V EXPERIMENTAL RESULTS 19

VI DISCUSSION OF RESULTS 33

VII EXTENSION OF CONCEPT TO POWER GENERATION 41

REFERENCES 45

APPENDICES

A ANALYTICAL TECHNIQUES, SPECIAL ANALYSES, AND EQUIPMENT . . 47

B RECORD OF EXPERIMENTS 56

FIGURES

1 Total Coal-to-Electricity Conversion Concept 7

2 Theoretical Cell Voltage Based on CO_2/CO Equilibrium 9

3 CO_2 Fraction for Various Temperatures and Pressures Calculated for the Equilibrium $C + CO_2 = 2\ CO$ 11

4 Illustration of Cell III 13

5 Current-Voltage Behavior of Graphite at Various Temperatures . . .21

6 Current-Voltage Behavior of Peabody Char at $973^{o}K$ 22

7 Current-Voltage Behavior of Pocahontas Coal 23

8 Current-Voltage Behavior of I linois No. 6 Seam Coal 24

9 Gas Composition with Time Behavior for Graphite 26

10 Gas Composition with Time Behavior for Graphite, Ash Contaminated 27

11 Gas Composition with Time Behavior for Peabody Char 28

12 Gas Composition with Time Behavior for Pocahontas Coal 29

13 Gas Composition with Time Behavior for Illinois No. 6 Seam Coal. .30

14 Flow Chart for Coal-to-Electricity System 42

15 Elution of Gases 49

16 Calibration Curves 50

TABLES

1 Open-Circuit Potentials Observed with Ash-Contaminated Electrolyte 20

2 Summary of Reaction Product Studies at 973°K 31

3 Elution Times and Estimated Detection Limits for Various Gases 51

4 Record of Experiments Performed 57

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This project was funded by the Environmental Protection Agency, Control System Laboratory, Research Triangle Park, North Carolina, whose support is gratefully acknowledged. Particular expression of gratitude is due Dr. John Smith, Chief, Engineering Analysis Branch, and Mr. Stan Bunas, Project Officer, both of whom greatly aided this project by their technical direction.

I CONCLUSIONS

The results of an initial study to determine the feasibility of the direct utilization of coal to produce electricity in a high temperature fuel cell are presented in this report. The system consisted of a molten carbonate fuel cell with an air cathode and a carbon anode, and the study concentrated on the anodic behavior of carbon in molten carbonate electrolyte. Satisfactory behavior was observed for anodes made from charred coal at temperatures of 975^{o}K and above. The potential efficiency of production of electricity in the molten carbonate fuel cell system was estimated to be more than one-and one-half times greater than that of a steam generator. The system can utilize coal in a nonpolluting fashion because the molten carbonate retains the pollutants from the coal.

The following conclusions can be made from this study:

- Carbon anodes can be successfully oxidized in a molten carbonate electrolyte.
- Satisfactory electrochemical behavior can be achieved at or above 975^{o}K (700^{o}C).
- The open circuit voltage of a cell with a charred coal anode/molten carbonate electrolyte/air cathode is about 1.1 v.
- Polarization of the anode is not excessive (200 mV or less at current densities above 100 mA/cm^{2}) at temperatures of 975^{o}K and higher.
- The presence of ash in the electrolyte does not impair performance of the cell.

- Carbon dioxide was observed as the principal product even though carbon monoxide is the thermodynamically favored product.

- A rough assessment indicates that the efficiency of generation of electricity might be as high as 1.65 times that of steam-electrical generators. (This value is based on a projection of fuel cell characteristics, see p. 44).

II RECOMMENDATIONS

The following are recommendations for future work:

- The study of the feasibility of the direct use of coal in a fuel cell should be continued and should be directed toward the development of an engineered system.

- Studies of factors influencing CO_2/CO ratios in product gas streams should be investigated.

- Attempts should be made to define conditions yielding CO_2/CO ratios of 10:1 or higher.

- Experimental cells should be used that will allow repeatable and precise correlation between the quantity of carbon used and the electricity produced.

- Further studies should be made of electrochemical behavior at various conditions to allow necessary design information for later engineering studies.

- Studies of ash on performance should be continued, with the use of pure carbon (not graphite) in pure electrolyte as a control reference.

- A study of matching air cathodes for use with the cell should be carried out in parallel with the above studies.

III INTRODUCTION

Coal is growing in its importance as a primary energy source for the United States; this importance increases as the total of energy sources is forecast for the next twenty or more years. Although coal is the most abundant of energy resources for the United States, the present technology for its use provides two undesirable and economically and ecologically unacceptable products: thermal and atmospheric pollution. The thermal pollution results from inefficiencies, imposed by Carnot limitations to heat engines, in the conversion of the energy content of the coal to electrical power. At best, as much heat is lost as is converted to electricity. Atmospheric pollution results when particulate matter (fly ash), oxides of nitrogen, and sulfur compounds are incorporated in flue gases.

A conceptual method for the more efficient conversion of the energy content of coal to electricity has long been known--electrochemical conversion. The work energy available electrochemically is equal to ΔG (the free energy of oxidation) whereas the work energy from heat engines is $\Delta H n_c$ where ΔH is the enthalpy of oxidation and n_c is the theoretical Carnot efficiency.*

---

* These are the standard thermodynamic terms for free-energy change, enthalpy change, and Carnot efficiency. The relationships are the familiar $\Delta H = \Delta G + T\Delta S$ and $n_c = Th - Tc/Th$. In practice n_c is about 0.4.

Since ΔG is not significantly different from ΔH for many reactions and n_c is generally about 0.4, the electrochemical energy available can be twice the energy available from heat engines.

These facts were taken into consideration in early studies of direct carbon fuel cells in which attempts were made to use carbon (from coal) in an electrochemical cell. The reaction desired was:

$$C + O_2 \rightarrow CO_2 + \text{electricity}$$

in which the oxygen would have been derived from air used as a cathodic reactant and the carbon would have represented coal as the anodic reactant. In the studies performed between 1900 and 1930, however it was demonstrated that, at the temperatures at which carbon provides satisfactory current densities, carbon monoxide rather than carbon dioxide is the principal product. Thus, full utilization of the energy content of the coal was not achieved.

The work done in that early period did show, however, that carbonate salts of the alkali metals in molten form served as chemically compatible electrolytes for the electrochemical cells. More recently, work on hydrogen and fuel-gas (methane, for example) fuel cells, using the molten carbonate electrolyte, advanced the air cathode to nearly satisfactory levels of performance. Thus, two essential parts of the cell system, the cathode and the electrolyte, had received adequate initial development by 1970. These developments were summarized by Liebhafsky and Cairns[1] and by Trachtenberg and Cole.[2]

The use of carbonate salts to avoid or eliminate air pollution from the stack gases of coal combustion systems has received recent attention with favorable results.[3] In terms of electrochemical cells for the use of coal, the use of molten carbonates thus offers the added advantage that pollutants would be trapped in the cell electrolyte rather than released to the air.

A concept for taking advantage of these facts was proposed by SRI as a means of efficiently converting coal to electricity by using fuel cells. The concept, shown schematically in Figure 1, consists of three major steps: (1) a coal/air fuel cell, (2) a water-gas shift reactor, and (3) a hydrogen/air fuel cell. The overall reaction for the entire process can be represented as:

$$C + O_2 \rightarrow CO_2 + \text{electricity} \qquad (1)$$

Because of the use of a fused-carbonate electrolyte, the proposed process for converting the energy of coal to electrical power promises to provide electrical power in a nonpolluting process.

The research reported here was undertaken to explore the feasibility of the concept just described. Except for the carbon anode of the carbon/air fuel cell, the technology for the three subsystems of the concept has been developed. Therefore, a laboratory study of the carbon anode in a carbonate electrolyte was undertaken.

The carbon/air fuel cell of interest involves chemical reactions at the anode (the carbon electrode) and at the cathode (the air electrode) in an electrolyte of molten alkali carbonates. The cathode reaction can be written as:

$$1/2\ O_2 + CO_2 + 2e^- \rightarrow CO_3^= \qquad (2)$$

so that the reversible voltage depends on the pressure of O_2 and CO_2 at the cathode. The anode reaction can be most simply represented by:

$$C + 2CO_3^= = 3CO_2 + 4e^- \qquad (3)$$

The anode reaction involves three oxidation states of carbon, and the equilibrium among those three states, namely,

$$C + CO_2 = 2CO \qquad (4)$$

must be considered in calculating the open circuit voltages. At low temperatures, the equilibrium lies to the left and the gas is mainly

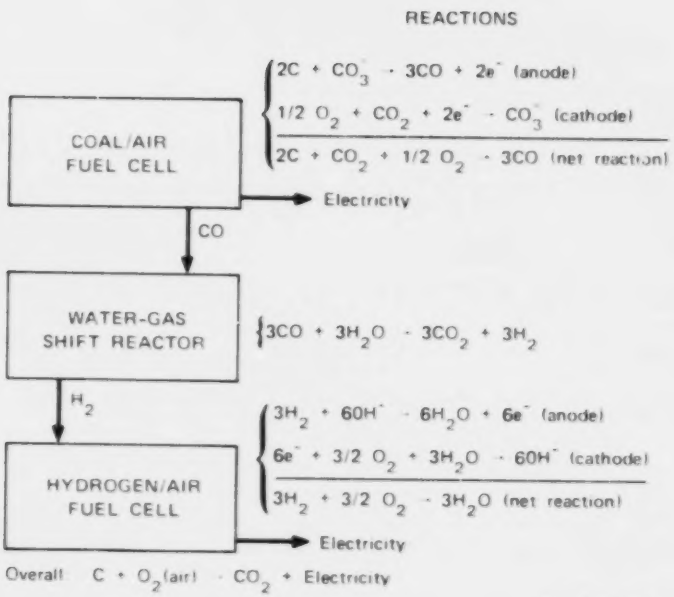
REACTIONS
COAL/AIR FUEL CELL
2C + CO_3^- → 3CO + $2e^-$ (anode)
1/2 O_2 + CO_2 + $2e^-$ → CO_3^- (cathode)
2C + CO_2 + 1/2 O_2 → 3CO (net reaction)
Electricity
CO
WATER-GAS SHIFT REACTOR
3CO + $3H_2O$ → $3CO_2$ + $3H_2$
H_2
HYDROGEN/AIR FUEL CELL
$3H_2$ + $6OH^-$ → $6H_2O$ + $6e^-$ (anode)
$6e^-$ + 3/2 O_2 + $3H_2O$ → $6OH^-$ (cathode)
$3H_2$ + 3/2 O_2 → $3H_2O$ (net reaction)
Electricity
Overall C + O_2 (air) → CO_2 + Electricity
SA 3547-25

FIGURE 1 TOTAL COAL-TO-ELECTRICITY CONVERSION CONCEPT

CO_2; at high temperatures, the gas is CO. Thus, it might appear that one should consider the anode reaction to be

$$2C + CO_3^{=} = 3CO + 2e^{-} \tag{5}$$

at high temperatures and

$$1/2\ C + CO_3^{=} = 3/2\ CO_2 + 2e^{-} \tag{6}$$

at low temperatures. However, it is sufficient to consider one anode reaction, i.e., Eq. (5), provided the equilibrium Eq. (4) is invoked to evaluate the partial pressure of CO at the anode.

The cell reaction can, therefore, be written:

$$2C + CO_3^{=} = 3CO + 2e^{-} \quad \text{(anode)}$$

$$2e^{-} + 1/2\ O_2 + CO_2 = CO_3^{=} \quad \text{(cathode)}$$

$$2C + 1/2\ O_2\ \text{(cathode)} + CO_2\ \text{(cathode)} = 3CO\ \text{(anode)} \tag{7}$$

The standard free energy change for reaction (7) can be calculated from literature data[4] to be

$$\Delta G^{o} = 14100 - 62.65\ T = -nFE^{o} \tag{8}$$

$$E^{o} = -0.3057 + 1.358 \times 10^{-3} T \tag{9}$$

Thus, the theoretical cell voltage is

$$E = E^{o} - \frac{RT}{2F} \log Q \tag{10}$$

$$E = E^{o} - 9.92 \times 10^{-5}\ T \log Q \tag{11}$$

in which

$$Q = \frac{p^{3}(CO,\ \text{anode})}{p(CO_2,\ \text{cathode}) \cdot p^{1/2}(O_2,\ \text{cathode})} \tag{12}$$

The theoretical cell voltages calculated are given in Figure 2. The E^{o} values were calculated from Eq. (9). The equilibrium CO pressures at the anode are calculated as discussed below. The O_2 and CO_2 pressures

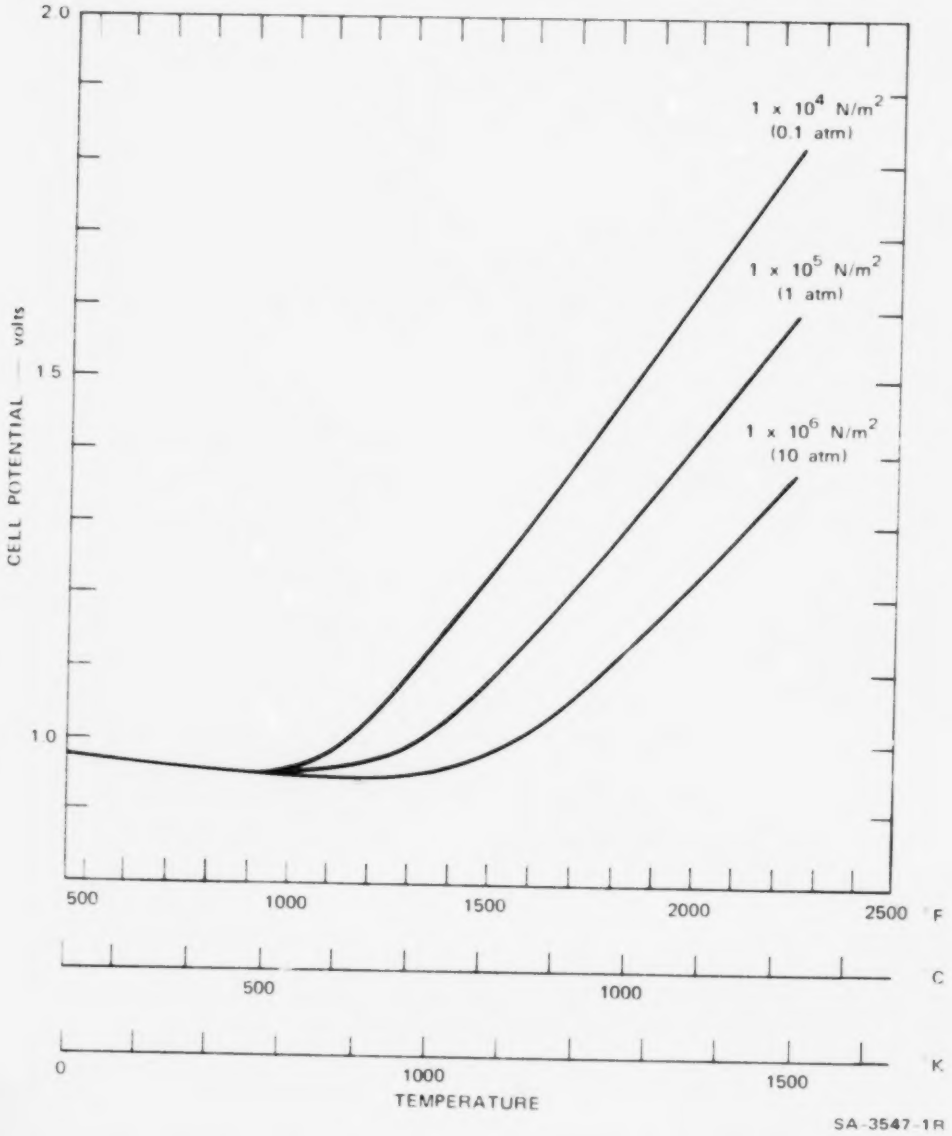

FIGURE 2 THEORETICAL CELL VOLTAGE BASED ON CO_2/CO EQUILIBRIUM

in the cathode were calculated for a mixture of 1/3 CO_2 and 2/3 dry air at the total cell pressure. The voltage is a nonlinear function of temperature and pressure because of the shift in the CO_2/CO equilibrium.

The fraction of CO_2 in the equilibrium vapor is shown in Figure 3. At low temperatures, the gas is predominantly CO_2; at high temperatures, it is predominantly CO. The ratio of CO_2 to CO is a function of temperature and pressure.

Although open-circuit voltages are a necessary test for proper performance, a more important criterion is voltage behavior while current is passing because the voltages calculated from thermodynamics will be modified by the kinetics of the reactions involved. As a practical guide, it was decided that if operation at current densities of 100 mA/cm^2 could be achieved at cell voltages near those predicted thermodynamically, feasibility would have been demonstrated.

Carbon can be anodically consumed to produce electricity in two ways as discussed above. If oxidized to form carbon dioxide, as in reaction (3), four Faradays of electricity per mole of carbon would be passed, together with the formation of three moles of carbon dioxide. If oxidized to form carbon monoxide, as in reaction (5), one Faraday of electricity would be passed with the formation of 3/2 mole of carbon monoxide. These relationships provide an additional test of the feasibility.

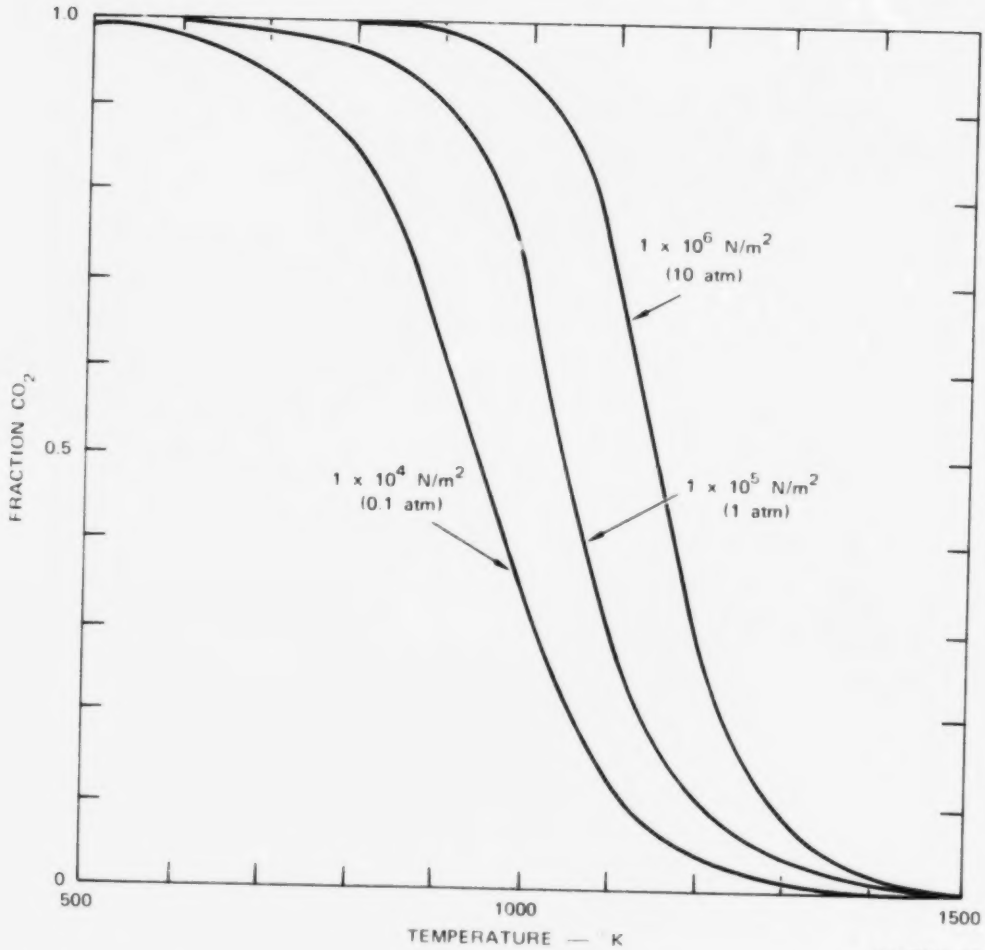

FIGURE 3 EQUILIBRIUM CO_2 FRACTION FOR VARIOUS TEMPERATURES AND PRESSURES

Calculated from the equilibrium $C + CO_2 = 2CO$

$$\log \frac{p^2(CO)}{p(CO_2)} \text{ (atm)} = -\frac{8919}{T} + 9.115$$

IV EXPERIMENTAL PROCEDURES

This section describes the various apparatus and procedures used in this study.

ELECTROCHEMICAL CELLS

During the course of this study, three cells of different designs were used. Cells I and II were useful only for measuring cell voltages because the anodes were not designed for collecting the anode gases. They were similar to cell III, except that the alumina container was open to the furnace atmosphere and cell I used a nickel counter electrode instead of graphite. Cell III was used to obtain almost all the results. Figure 4 presents a schematic diagram of cell III; its components are described below.

Working electrode

Anode materials - Graphite, coal char, and charred coals

Dimensions - Graphite, 0.64-cm diameter, 30.5-cm long, immersed 1 cm in melt

Coals, approximately 2-cm long, 1.5-cm wide, and 0.8-cm thick

Gas atmosphere - He plus CO_2 and CO generated by reaction with the melt

Counter electrode

Spectrographic graphite rod 0.635 cm diameter x 30.5 cm long

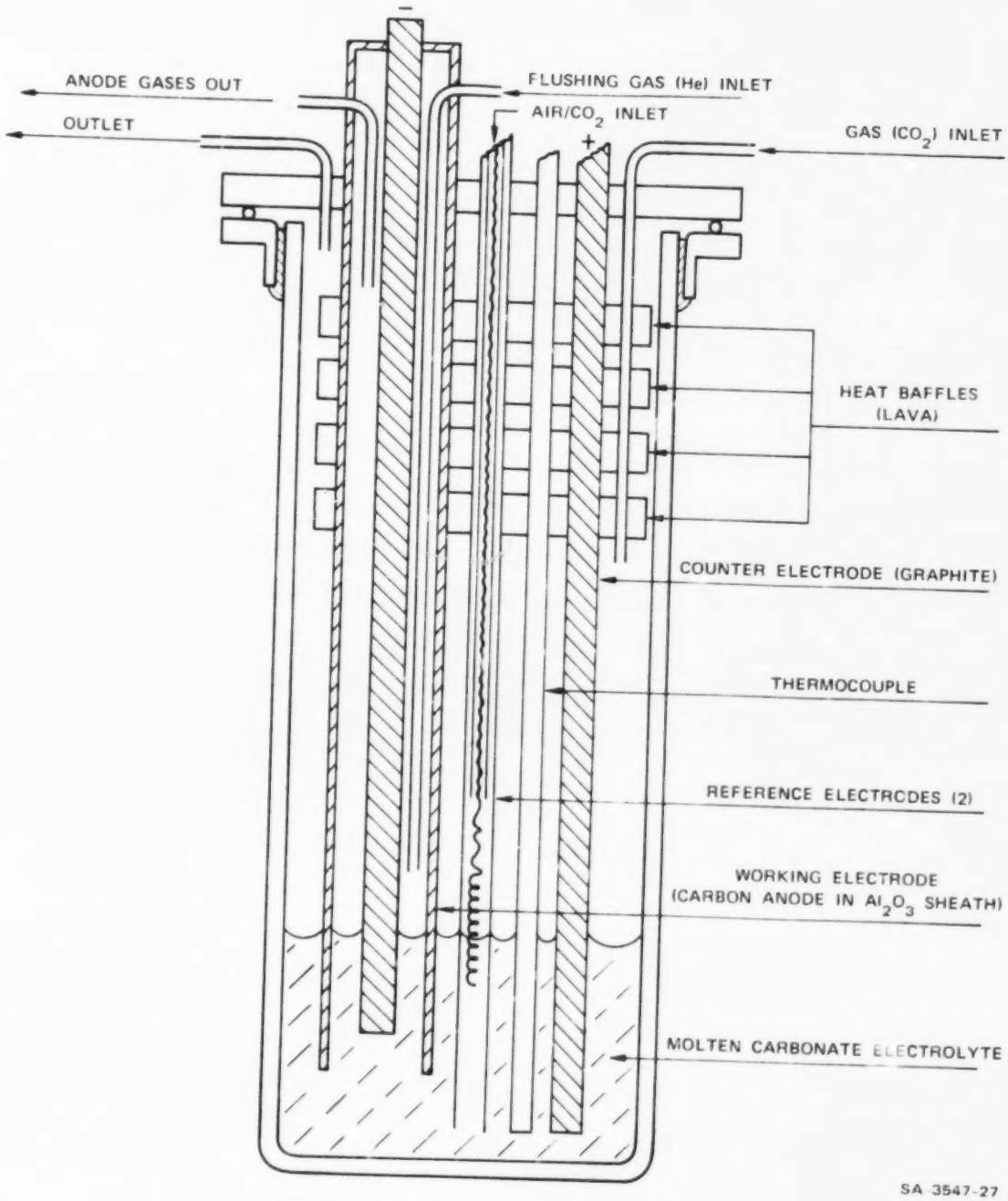

FIGURE 4 ILLUSTRATION OF CELL III

Counter electrode gas environment

Helium was used up to run III-E, then changed to CO_2 to prevent cathodic deposition of alkali metals in all subsequent runs.

Reference electrodes

Two separate electrodes were used, consisting of a gold or silver wire coil dipping into the melt and flushed with a slow stream of CO_2 (33%) plus air (67%).

The cells were heated in an electrical resistance furnace equipped with temperature controls actuated by thermocouples.

ELECTROLYTE AND ASH

The electrolyte used was the ternary eutectic of sodium, potassium, and lithium carbonates in a 3:3:4 mole ratio. The carbonates were ACS grade reagents, used as received without drying before use in the cell. Studies of ash contaminated electrolytes were made by adding 10 wt % of fly ash to the electrolyte. Spectrographic analysis of the fly ash is given in Appendix A.

REFERENCE ELECTRODES

Reference electrodes for use in carbonate melts have been described by Borucka and Sugiyama[5,6] and by Appleby and Nicholson.[7] The electrodes used in the present work were similar. The half cell reaction occurring was expected to be

$$2e^- + \tfrac{1}{2}O_2 + CO_2 = CO_3^= \qquad (13)$$

The partial pressures of O_2 (0.14 atm) and CO_2 (0.33 atm) were kept constant by a small flow of air-CO_2 mixture through the electrode. Since the literature mentions both silver and gold as suitable electrodes, one reference electrode of each was included in the cell. We found no real difference in the performances of the two reference electrodes, although performance was often erratic for unknown reasons.

ANODES

Studies of pure carbon in the form of graphite were made using spectroscopic grade electrodes, 0.635 cm in diameter.

Studies on charred coal were made on samples of four types of coal: Peabody char, Pocahontas, Decker Main and Illinois No. 6 seam coal. Analyses are presented in Appendix A. The samples of the already-charred coal (Peabody char, Western Kentucky coal, No. 9) were used as electrodes by forming a lump to approximately a rectangular solid, 2-cm long, 1.5-cm wide, and 0.8-cm thick. A hole was then drilled in the end of the bar, a 0.05-cm diameter platinum wire was placed through the hole, and both ends of the wire were passed through an Al_2O_3 tube of 0.64 cm o.d. When pushed toward the sample of char, the alumina tube tightens the platinum wire, assuring electrical contact. The alumina tube was brought to the cold regions of the cell assembly where electrical contact to internal cell circuitry was made through the ends of the platinum wire.

The coal samples were charred by two techniques. The first involved heating the sample in a helium atmosphere to 825^{o}K at a controlled rate of 3 degrees per minute. The second involved placing a sample of crushed and sieved coal in a small fused-silica tube. A length of the 0.05-cm-diameter platinum wire, wrapped at the end into a helix, was centered in the tube before addition of the crushed coal. The tube, containing the platinum wire and coal was then heated with a torch to a red heat (estimated 1300^{o}K). The total time for heating was approximately five minutes. This destructive distillation technique was stopped when evolution of volatile matter ceased and the carbon had been heated to a red heat. During the heating, a fused silica rod, placed over the protruding platinum wire, was pressed against the top of the coal sample to prevent expansion of the coal. Charred-coal electrodes

so prepared slipped easily from the fused silica tube and retained the dimensions of the tube's diameter.

The graphite electrode was submerged in the electrolyte about two centimeters, which exposed about 4 cm^2 of surface to the melt. The coal electrodes as formed had a diameter of 0.95 cm and were submerged about 2 cm so that about 5 cm^2 of geometric surface was in the melt. The true electrochemical area was difficult to determine, however, because the samples were honeycombed by large pores.

GAS AND GAS-FLOW CONTROL SYSTEMS

Commercial helium was used in the anode. Traces of oxygen were removed by passing the gas over copper metal heated to 725°K, and moisture was removed by passing the gas through a molecular sieve drying tube (Linde 5A, dried under vacuum at 400°C) at room temperature. The air-CO_2 mixture was dried over molecular sieve. CO_2 was a commercial dry grade and was used directly from the cylinder.

Flow rates were calibrated by observing soap-bubble movement in a burette inserted in the line as needed. Flow rates were monitored by glass-ball flow-meters.

GAS ANALYSES

All gas analyses were performed with a dual-column gas chromatograph. Details of the equipment are presented in Appendix A. Samples of gases to be analyzed were extracted using Hamilton Company Gas-Tight syringes. The usual sample size was 1 cm^3. Calibration curves for CO_2 and CO were checked daily, and results obtained were accurate to within ± 2%.

ELECTROCHEMICAL ANALYSES

A list of the equipment most frequently used in the studies is presented in Appendix A. Study of the electrochemical performance of the

anodes required measurement of anode versus reference potentials, the current, and the polarization with current. Techniques used for these measurements are described below.

Potential Measurements

The potential of the anode versus the reference electrode was monitored with one channel of a strip-chart recorder. Assurance that source resistance did not introduce errors was achieved by use of the electrometer or by measurement of resistance by pulse techniques. The electrometer was used for this purpose by varying its input impedance. If no change in indicated voltage occurred at input resistances to one decade below the minimum of the recorder, that is, down from 10^{11} ohms to 10^{3} ohms, then it was accepted that the recorder presented accurate potential readings. Pulse techniques are described below under polarization measurements.

Polarization Measurements

The voltage behavior of the anode with various levels of current was studied under steady-state and transient (pulse) conditions. Steady-state behavior at various levels of current was studied by adjusting the current to desired levels, either by adjusting the programmable power supply or by adjusting the potentiostat in the galvanostatic mode. The potential of the anode versus the reference was recorded on a strip-chart recorder. An alternative method, and one consuming less operator time, was to program the potentiostat in the galvanostatic mode to follow a linear change in signal with time. This signal was generated by the waveform generator. At very low sweep rates, requiring 16 minutes to vary the current from zero to the desired upper current limit, the results were in agreement with the manual steady-state technique. Since the data obtained in this programmed mode were recorded on an x-y recorder using the current and voltage analog outputs from the

potentiostat, they directly produced the polarization curves.

Measurement of resistance and activation polarization require fast-response pulse techniques. An oscilloscope was used to monitor voltage behavior with time when the current was abruptly (less than 3 microseconds) changed from one level to another. Resistance values were also obtained from the slope of the I-V polarization curves, discussed above, and by use of an ac resistance bridge.

TYPICAL PROCEDURE

The procedure used to study the anodic behavior of carbon was as follows. The assembled cell, equipped with all gas and electrical connections and already containing the correct amount of electrolyte and the anode under study, was raised from an idling temperature of about 773°K to the temperature desired for the study. Two to four hours were required to reach and stabilize the temperature. During this time, the flow rates of gases from the components of the cell were checked, the chromatograph was readied for analysis, and chromatographic response was checked against previously established calibration curves. If measurements to correlate gas composition and rate with current were desired, it was necessary to wait until a steady-state background for the gases was attained. If the anode had been studied previously, this steady state was sometimes reached in as little as two to four hours. If the anode was newly prepared, however, or if the temperature change made was extreme (e.g., 1100-1200°K), longer periods were required.

Correlations of gas kind and evolution rate with various current levels were undertaken after steady-state gas composition had been reached. After the particular study was completed, the temperature of the cell was lowered to 773°K. The temperature of the cell was not allowed to cool to the freezing point of the electrolyte.

V EXPERIMENTAL RESULTS

Studies of the electrochemical oxidation of carbon electrodes in a molten carbonate electrolyte were made with various carbons and at various temperatures, both with pure electrolyte and with electrolyte containing 10% ash. The studies included the voltage of the carbons relative to a reference electrode, which was essentially equivalent in potential to the potential expected with an air cathode in a complete cell. The electrochemical behavior during passage of significant current was also studied.

POTENTIAL MEASUREMENTS

The voltages observed between the various carbon electrodes and the reference electrode are presented in Appendix B. The values were often erratic, but the erratic behavior could generally be traced to the reference electrode; that is, the voltage between the working anode and the graphite counter electrode was generally stable even when the anode-reference voltage was erratic. The last eight runs with cell III (P to W) seemed to have stable open circuit voltages. These values are collected in Table 1, together with some of the earlier, erratic values.

CURRENT-VOLTAGE BEHAVIOR

The polarization of the carbon anodes was studied under various conditions of current drain and sweep rate (rate of change of current) as well as temperature and kind of carbon. The currents were controlled by a programmable potentiostat and were recorded versus voltage on an x-y recorder. Sweep rates were limited by the response of the recorder to about 200 mA/sec. Representative results are presented in Figures 5 through 8.

Table 1

OPEN-CIRCUIT POTENTIALS OBSERVED WITH
ASH-CONTAMINATED ELECTROLYTE

Anode	Run No.	Temperature (°K)	Open-circuit Voltage[a] (volts)	Theoretical Voltage (volts)
Graphite	III-I	793	-0.81	-0.95
	III-J	973	-0.65	-0.99
	III-K	1168	-0.47	-1.17
	III-L	983	--	-0.99
	III-M	981	-1.07	-0.99
	III-N	973	-0.74	-0.99
	III-O	1169	-0.86	-1.17
Peabody char	III-P	877	-1.10	-0.96
	III-Q	833	-0.96	-0.96
	III-R	1043	-1.08	-1.04
	III-S	971	-1.12	-0.99
	III-T	982	-1.08	-0.99
Pocahontas	III-U	985	-1.10	-0.99
Illinois No. 6 seam	III-V	974	-1.13	-0.97
	III-W	973	-1.09	-0.97

[a]Reference electrode behavior was erratic during Runs III-I through III-O. Voltages were stable and repeatable during Runs III-P through III-W.

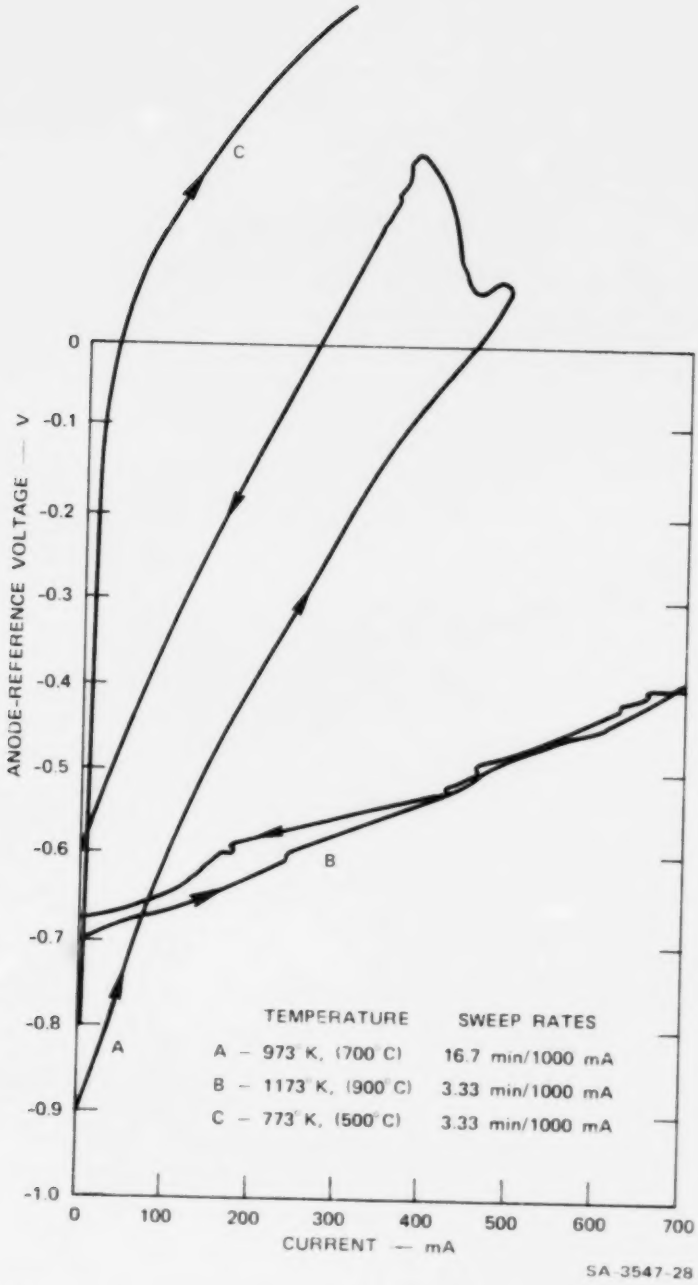

FIGURE 5 CURRENT-VOLTAGE BEHAVIOR OF GRAPHITE AT VARIOUS TEMPERATURES

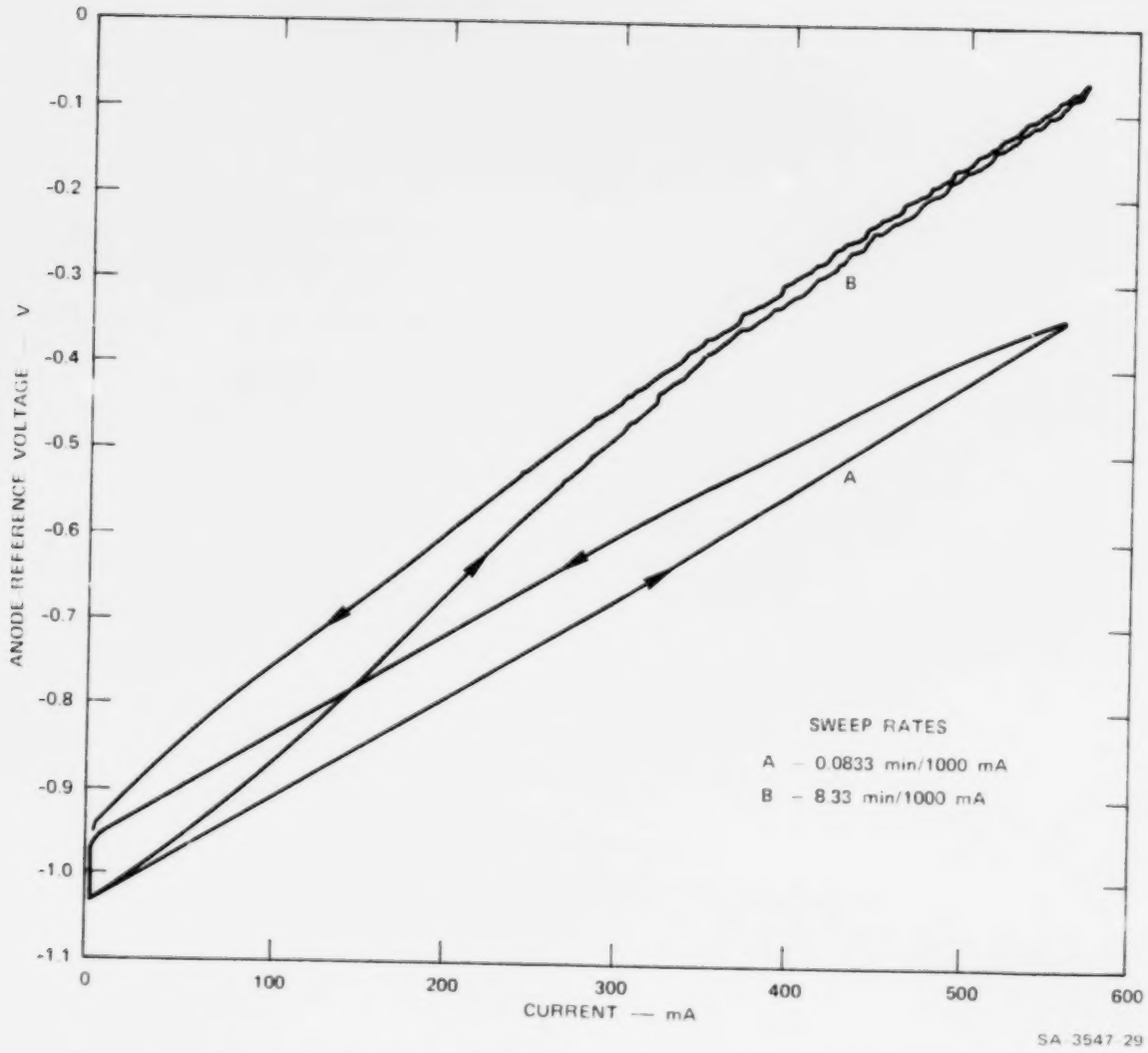

FIGURE 6 CURRENT-VOLTAGE BEHAVIOR OF PEABODY CHAR AT 973°K

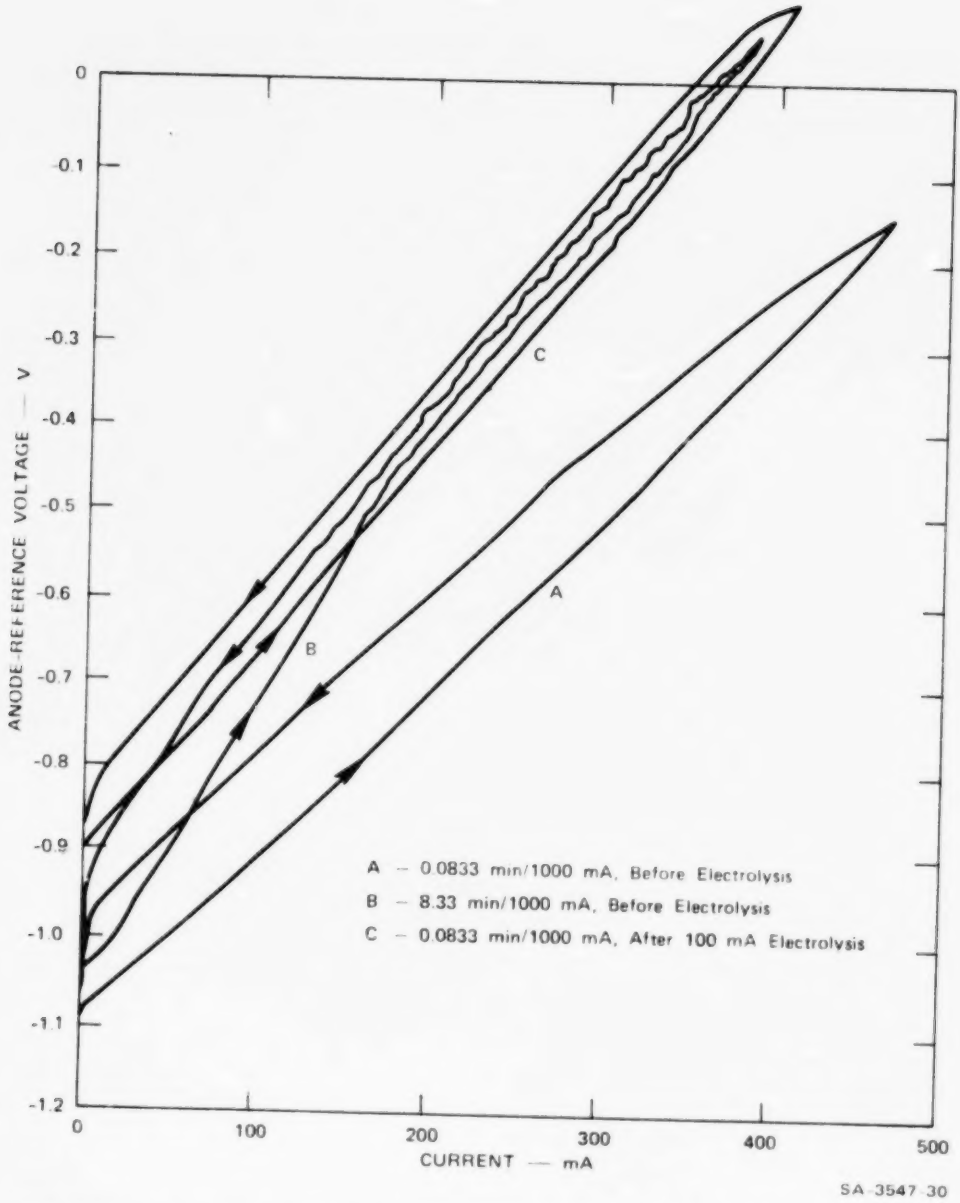

FIGURE 7 CURRENT-VOLTAGE BEHAVIOR OF POCAHONTAS COAL AT 973°K

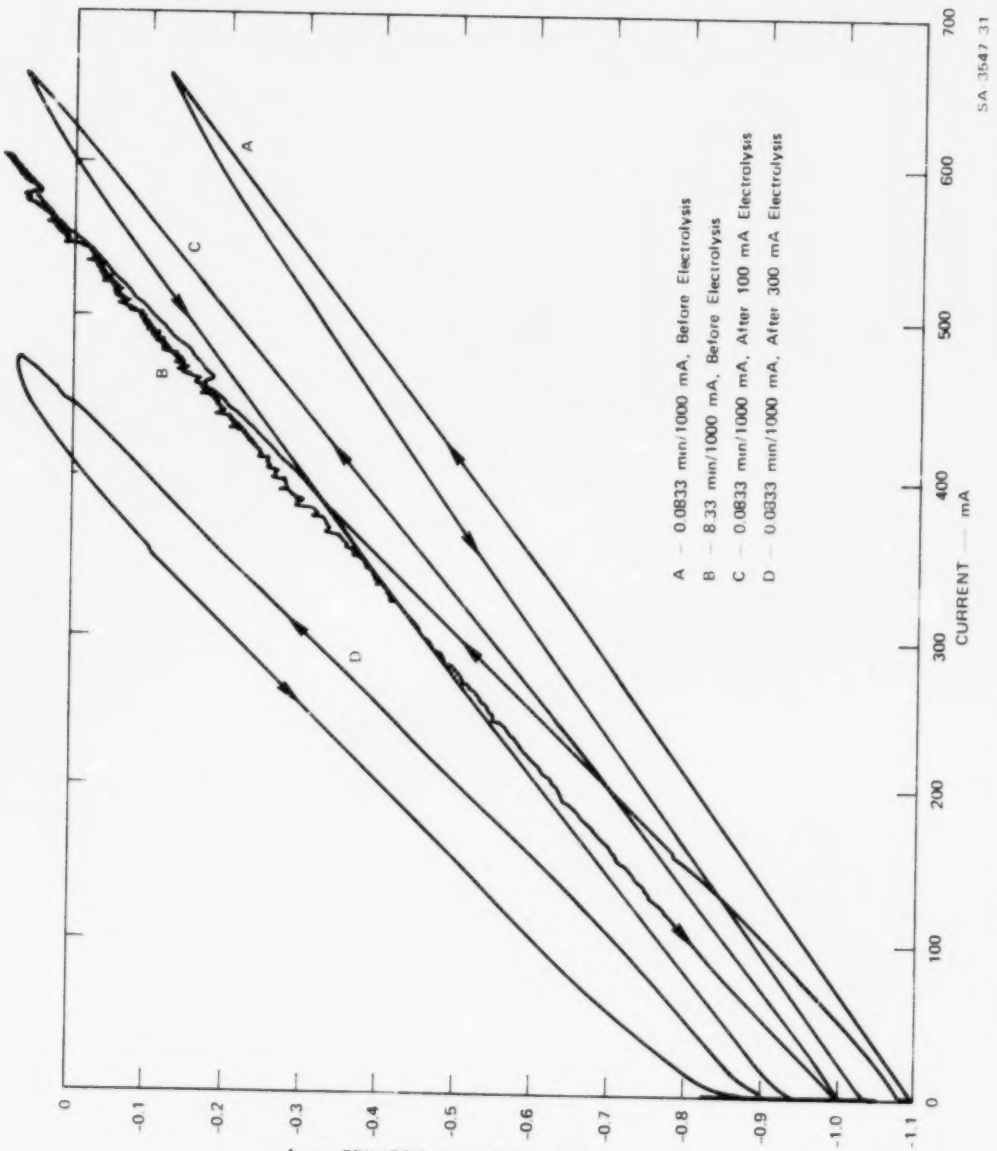

FIGURE 8 CURRENT-VOLTAGE BEHAVIOR OF ILLINOIS NO. 6 SEAM COAL AT 973°K

STUDIES OF REACTION PRODUCTS

The rates at which CO and CO_2 were generated by electrolysis were measured as described. Electrolysis corresponded to the anodic (oxidative) electrode reaction of coal and, therefore, to the discharge of a coal/air fuel cell. Examples of the variation of concentration of gases with time for the various samples are presented in Figures 9 through 13. Results of the reaction-product studies are given in Appendix B. The information on coals is summarized in Table 2.

CELL AUTOPSY

The cell had been maintained continuously at temperatures at or above 773°K for more than five months. During this time, the alumina cell components were in contact with the fused-carbonate electrolyte. During the last two months, the electrolyte was contaminated with fly ash. The cell was disassembled on termination of the study, and the parts were examined.

On autopsy, a crack was discovered in the outer alumina tube. The crack was small and coincided exactly with the end of the heating element in the furnace. The surfaces of the alumina that had been exposed to the electrolyte showed no evidence of chemical attack or staining. The effect due to this crack is not known.

Most of the electrolyte could be poured from the cell while the temperature was above the melting point. The electrolyte that remained in the cell was dark and was clearly highly contaminated with the fly ash. Polarographic analysis of the dark electrolyte showed that it contained approximately 2 wt% of $Fe_2(CO_3)_3$ and 0.5 wt% of $FeCO_3$. The electrolyte that was poured from the cell was white and showed no evidence of colored particulate matter dispersed within it. The concentration of reducible species was undetectable in the white samples. It follows, therefore, that most of the ash was insoluble in the electrolyte and settled to the bottom of the cell.

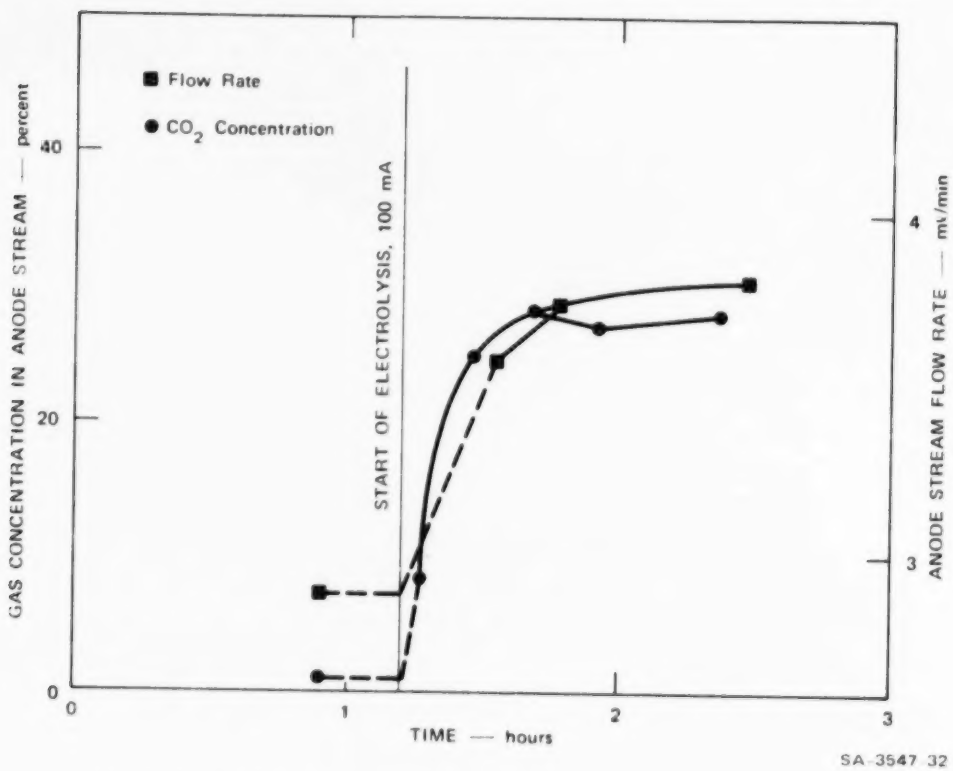

FIGURE 9 GAS COMPOSITION WITH TIME BEHAVIOR FOR GRAPHITE AT 973°K (RUN III-F)

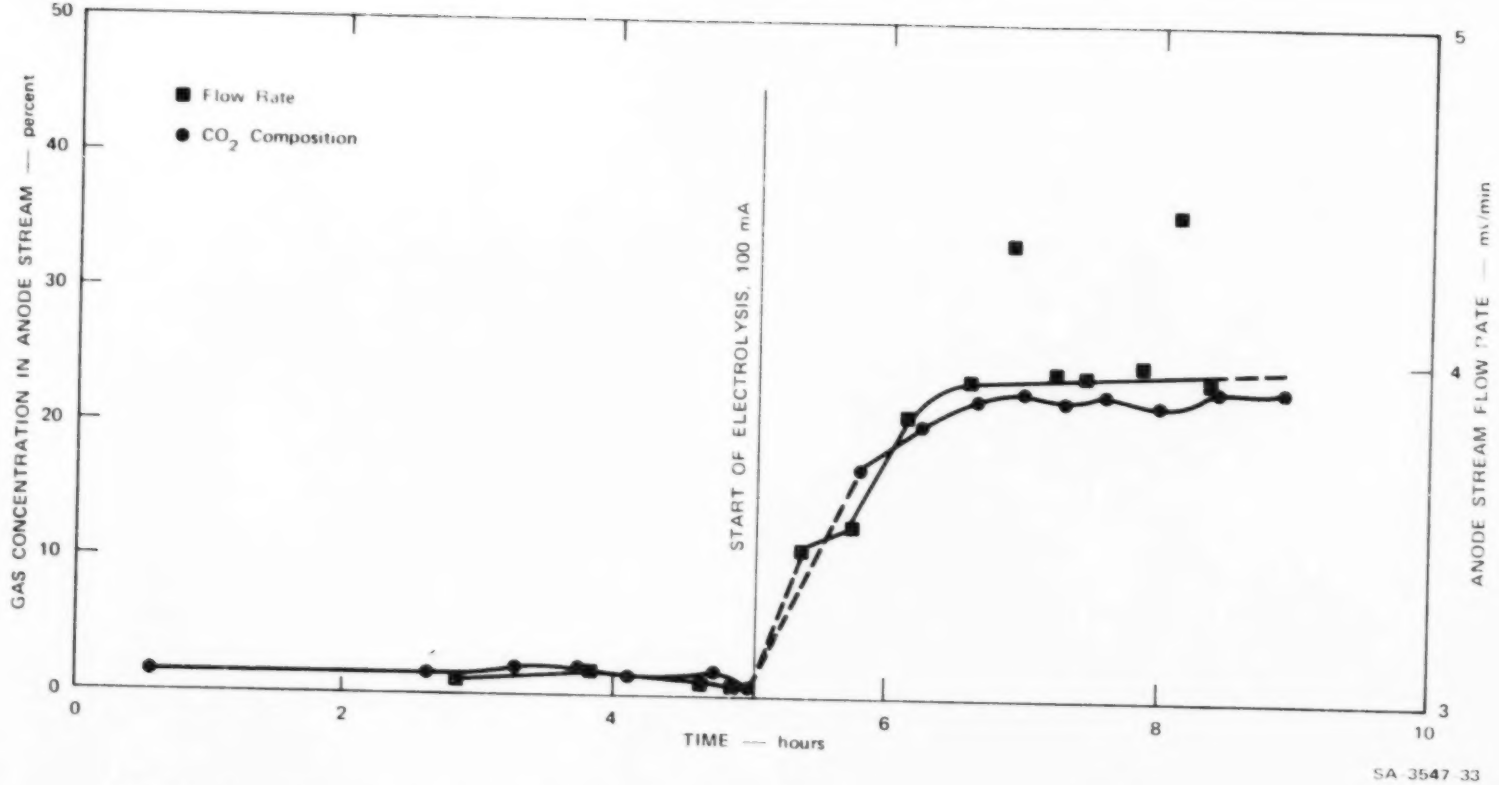

FIGURE 10 GAS COMPOSITION WITH TIME BEHAVIOR FOR GRAPHITE, ASH-CONTAMINATED ELECTROLYTE, AT 973°K (RUN III-N)

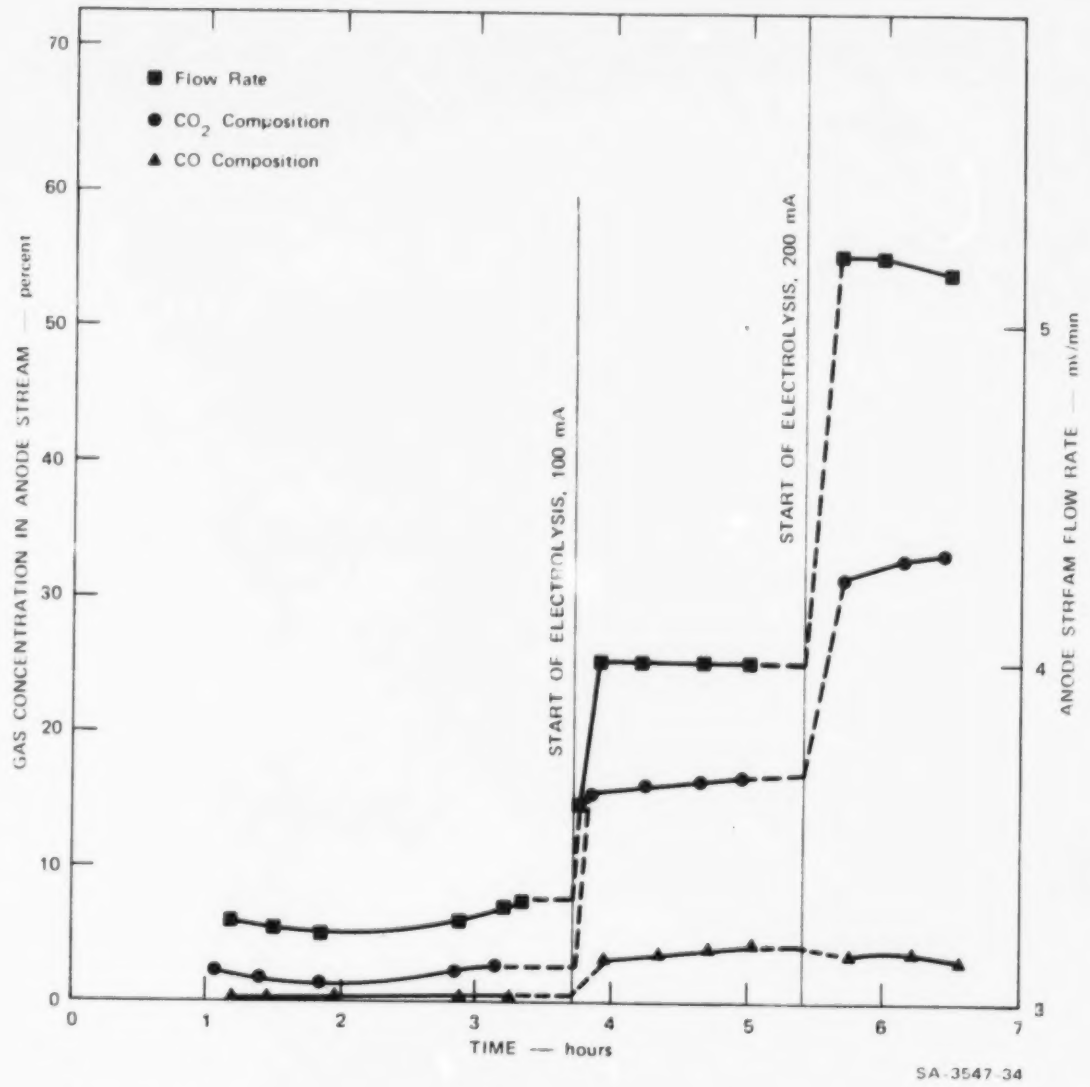

FIGURE 11 GAS COMPOSITION WITH TIME BEHAVIOR FOR PEABODY CHAR AT 982°K (RUN III-T)

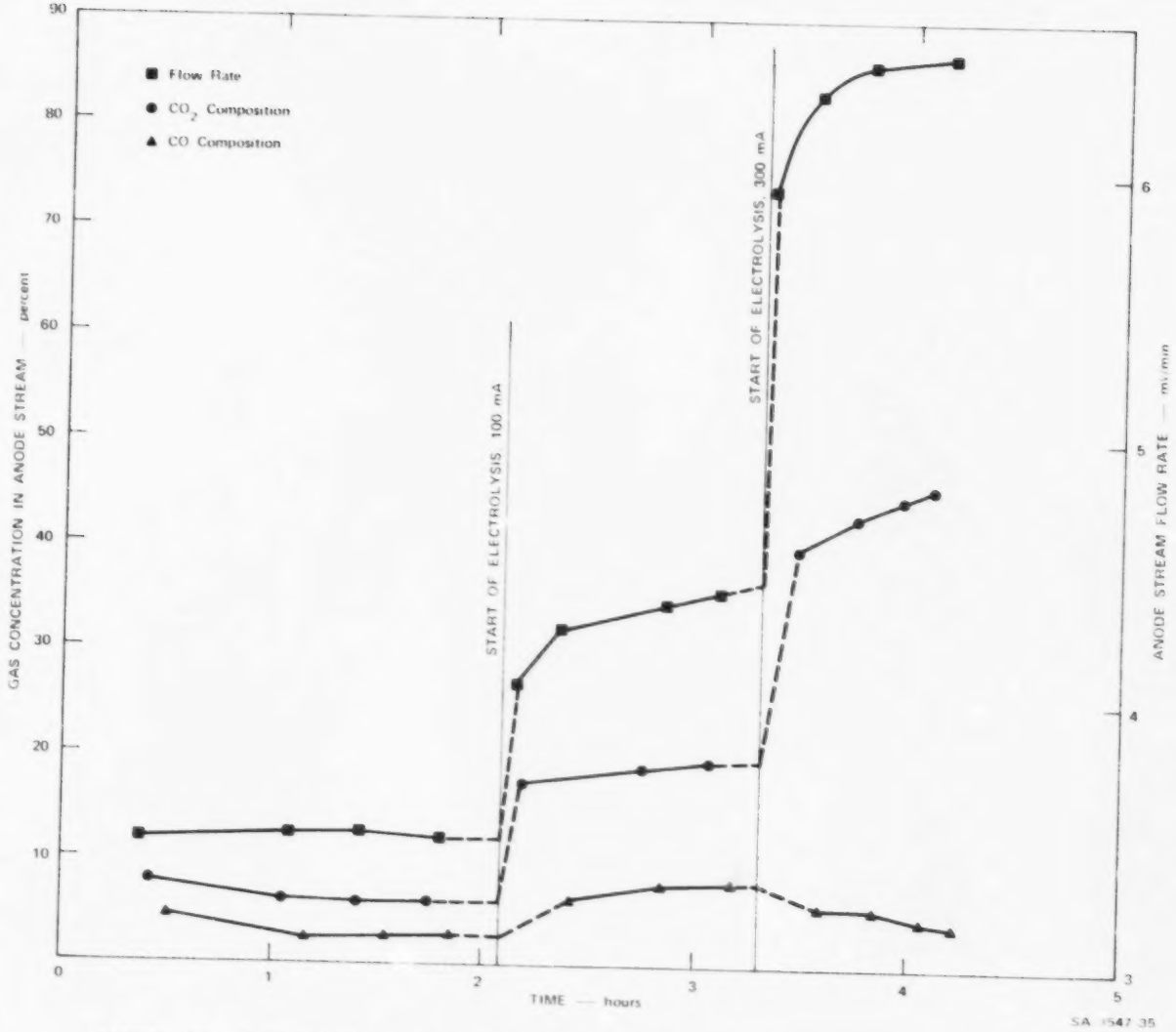

FIGURE 12 GAS COMPOSITION WITH TIME BEHAVIOR FOR POCAHONTAS COAL AT 985°K. (RUN III-V)

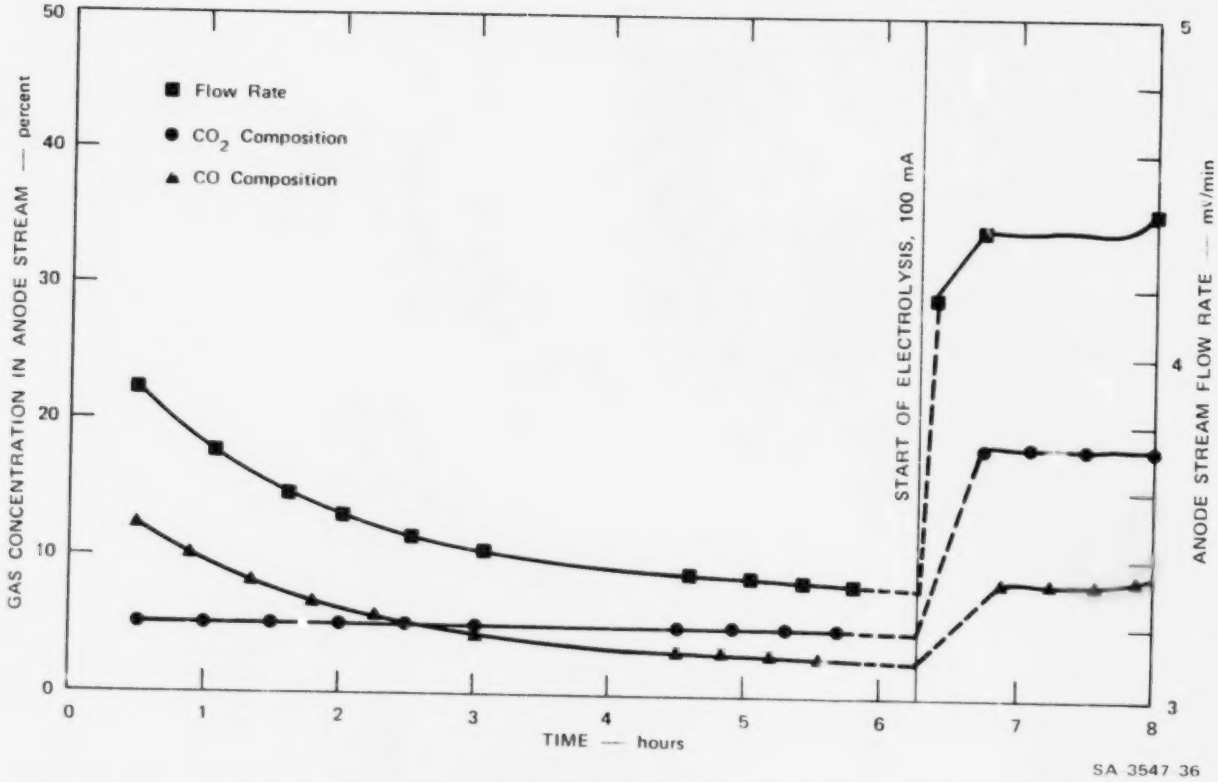

FIGURE 13 GAS COMPOSITION WITH TIME BEHAVIOR FOR ILLINOIS NO. 6 SEAM COAL AT 974°K (RUN III-V)

Table 2. SUMMARY OF REACTION PRODUCT STUDIES AT 973°K (700°C)

Anode	Run No.	Steady-state gas concentration during electrolysis			Electrolysis current mA	Current Efficiency %**
		CO_2 fraction*	CO fraction*	Ratio CO_2/CO		
Graphite, pure electrolyte	III-F	0.290	0.001	--	100	95
Graphite, ash-contaminated electrolyte	III-M,N	0.223	0.003	75	100	70
Peabody char	III-T	0.161	0.037	4	100	60
	III-T	0.324	0.034	10	200	75
	III-U	0.192	0.078	2	100	65
	III-U	0.445	0.049	10	300	80
Illinois No. 6 seam coal	III-V	0.183	0.082	2	100	70
	III-W	0.441	0.048	9	300	75

* balance helium

** current efficiencies calculated from $CE\% = 100\left(\frac{2.66 \times \text{fraction CO} + 5.32 \times \text{fraction } CO_2}{\text{current, amps}}\right)\left(\frac{\text{gas flow ml/min}}{60}\right)$

Samples of the black residue of electrolyte and ash from the bottom of the cell were extracted in a Soxhlet extractor with concentrated hydrochloric acid. A white gel, presumably silica resulting from the ash, was found as an insoluble constituent.

The samples of charred coal electrodes were weighed before and after electrolysis studies. The weight loss should be correlatable with the known quantity of electrochemical charge passed through the electrode. However, due to attack by the CO_2 dissolved in the electrolyte or by mechanical loss, the weight losses observed were one order of magnitude larger than those calculated on the basis of the known charge passed.

VI DISCUSSION OF RESULTS

The purpose of the research was to observe the performance of carbon anodes derived from coal in a carbonate melt to assess the feasibility of direct utilization of coal electrochemically. The important factors for that purpose are:

- Cell voltage under current drain
- Effect of temperature
- Current efficiency
- Gases produced (CO or CO_2)
- Effect of ash

With the limited funds available it was possible to evaluate only general trends in cell behavior with respect to these factors.

In general, the carbon anodes behaved surprisingly well, and better than graphite anodes. The erratic behavior of the reference electrodes caused the greatest electrochemical difficulty, but there was no time to spend on improving their performance. The mechanical operation of the cells was relatively straightforward but could be simplified by better design. The biggest problem was the small leaks that occurred in the anode gas-handling system. There was no problem with container materials; alumina seemed unattacked after hundreds of hours of operation.

OPEN CIRCUIT VOLTAGES

The most reliable operation of the reference electrodes was observed in the last eight runs (III-P to III-W) during the time that the various charred coals were tested in the ash-contaminated electrolyte. These open circuit voltages, given earlier in Table 1, were generally about -1.1 volts, which is about 0.1 volt greater than theoretical for graphite. The greater value may be due to the fact that the carbon in charred coal is in a thermodynamically less stable state than graphite. It is well known that the heat of combustion of coke or amorphous carbon is greater than that of graphite.[8]

Theoretical calculations indicated that above about 1000°K the open circuit voltages should become larger. With graphite in the absence of ash, the voltages did increase with temperature (see results of cell II in Appendix B). Because the charred coal anodes showed acceptably small polarizations at about 970°K, they were not studied at higher temperatures.

The voltages observed with graphite before and after ash addition were not significantly different, although both were uncertain because of poor reference electrode behavior. Therefore, to a first approximation at least, the ash added to the electrolyte had no effect on open circuit voltage. This result tends to be corroborated by the fact that the open circuit voltages observed in runs with ash present on charred coals (Runs III-P to III-W) were greater than theoretical.

POLARIZATION STUDIES

Three phenomena tend to reduce cell voltage when current is passed: activation polarization, concentration polarization, and IR drop due to cell resistance. These phenomena are influenced in different ways by sweep rate during polarization and by cell temperature, and they can be

modified to different degrees by cell design. For example, activation polarization reflects a slowness in the chemical reactions occurring at the electrode surface. It is a strong function of temperature, decreasing with increased temperature and possibly mitigated by catalysts.

In the present work, the charred coals showed an acceptably small activation polarization at about 1000°K. The resistance or IR drop is not so sensitive to temperature but is dependent on geometrical factors in the cell. Th cell resistance was about 0.5 ohm in the present studies, as measured by fast response (oscilloscope) techniques. Polarization due to concentration effects was observed in some cells. Presumably a difference in concentration of some ion(s) between the anode and reference electrode was generated by passage of current. This effect decreased with increase of temperature as expected (because diffusivities of ions increase with temperature).

The results of polarization studies were illustrated earlier in Figures 5 to 8 for triangular-sweep voltametry and by the voltages observed during 100 mA electrolyses reported in Appendix B. The behavior of graphite is shown in Figure 5. The curve at 1173°K, except for the erratic reference electrode, is essentially linear with little hysteresis, which indicates that IR drop is the predominant source of polarization. The slope of the curve is in accord with the 0.5-ohm cell resistance. At 973°K the substantially larger slope indicates polarization other than IR, and the hysteresis of the curve implies that there is significant concentration polarization. At 773°K the polarization is severe.

For the charred coals at 973°K, the fast sweep rate curves (curve A of Figures 6, 7, 8) showed a small degree of hysteresis and a slope slightly larger than that corresponding to 0.5 ohm. After a correction for IR drop, the polarization (activation plus concentration) amounted

to about 0.08, 0.15, and 0.1 volts at 100 mA for Peabody char, Pocahontas, and Illinois No. 6 respectively.

The presence of concentration polarization with the charred coals at 973°K is shown by the shift in the curves (from A to B in Figures 6, 7, and 8) as sweep rate decreased. At the lower sweep rates, the electrolysis time to reach a given current was greater as was the concentration of electrolysis product. Also the curves immediately after electrolysis (curves C of Figures 7 and 8) are shifted in the same direction, again indicating the effects of concentration. Some indication of changing surface character (activation effects) were observed in the scan taken after electrolysis.

The extent of steady-state concentration polarization did not alter significantly as a result of extended electrolysis, as shown in Figure 7. The slow-rate study of concentration polarization taken before electrolysis (curve B) is essentially the same as the fast rate response, curve C, taken after several hours of 100-mA electrolysis. Therefore, even though the anode area may have changed somewhat during the electrolysis, and the composition of the electrolyte might have been expected to change, neither seemed to cause a noticeable change in concentration polarization behavior.

The same behavior is displayed in Figure 8, in which curves A, B, and C correspond to data taken for Run III-V at 100 mA. The level of concentration polarization does change with the level of current, as shown by curve D, which was obtained after a 300-mA electrolysis and which shows greater polarization than observed at 100 mA.

To relate the observed polarization effects to large scale cell operation, it is necessary to convert the effect of current to current densities. That is, the effective electrode areas need to be known. It was estimated that the geometrical anode surface exposed to the melt

was about 4 to 5 cm^2. However, the tips of the electrodes are expected to have a much greater current density than the sides. It is difficult to calculate the exact distribution of the current. From consideration of the geometry and current paths involved, we estimate that the anode surface area was 2 ± 1 cm^2 for purposes of scaling current densities.

CURRENT EFFICIENCY

The efficiency of conversion of the available energy of carbon to electrical energy is a product of two terms: the voltage efficiency and the current efficiency. The voltage efficiency depends on the activation, concentration, and resistance polarization terms, as discussed above. The current efficiency is a measure of how effectively the material is being used to produce electricity. As indicated by equations (5) and (6) in Section III, the quantity of electricity produced (moles of electrons) per mole of carbon consumed, depends on the course of the reaction, which, in turn, is indicated by the nature and amount of the products.

Thus, four Faradays of electricity are produced if a mole of carbon is oxidized to CO_2, while only one is produced if CO is the product. Therefore, an important aspect of this study was to determine the amounts of CO and CO_2 produced at the anode during electrolysis.

The current efficiencies and relative amounts of CO and CO_2 for all the runs are shown in Appendix B. The results of some representative runs were shown in Figures 9 to 13, and the results for the charred coals were summarized in Table 2.

The first few runs with cell III (A to D) were made with helium in the cathode compartment. When current efficiencies fell to very low values, it was realized that the $CO_3^=$ of the melt had been depleted and that the melt must have become an electronic conductor by formation of

alkali metal. When CO_2 was passed into the cathode, the current efficiency rose to essentially 100%.

The measured current efficiencies were very sensitive to small gas leaks in the anode gas-handling line. In Runs III-L and III-O, the low current efficiencies were caused by such leaks. In some of the other runs, the current efficiency was somewhat less than 100% and averaged about 75%. Low current efficiencies can arise from either mechanical losses in the cell due to poor design (i.e., leaks in the anode gas handling system or the escape of bubbles from the bottom of the anode out into the cathode region rather than into the anode sheath) or from physicochemical processes (i.e., electronic conduction by the melt, or chemical shuttle mechanisms in which anode products diffuse to the cathode and are reduced). Limitation of time and funds prevented us from exploring the true reason for the less than 100% current efficiency.

The ratio of CO_2 to CO in the anode gas for all runs is shown in Appendix B. The ratio during electrolysis was always larger than expected from the equilibrium values shown in Figure 3. The most important results pertained to the charred coals, as summarized in Table 2. The equilibrium CO_2/CO ratio at 975°K is about 0.3 (dependent somewhat on the total pressure of CO_2 plus CO). The observed values were from 7 to 30 times as large. It is also apparent that the CO_2/CO ratio increased with increased current density, and it was larger for graphite than for the charred coals. These results indicate that the greater the degree of irreversibility of the electrochemical oxidation, the larger the CO_2/CO ratio. This fact is important for projection to industrial scale operation because it indicates that the greater the current density, the more effective will be the utilization of the char (i.e., the more complete its combustion).

The results also imply that the process of charring the coal may be altered so as to result in chars that are electrochemically more active and therefore give higher cell voltages by 10 to 100 mV.

The high CO_2/CO ratio in the cells studied is in accord with observations in the electrolysis of aluminum. In the aluminum industry, carbon (Soderberg electrode) is anodically oxidized in a molten salt (cryolite) at high temperatures. The conditions for that process differ from the present anodic carbon oxidation in two ways: the temperature is higher ($\sim 1300^{o}K$), and the melt has a much lower oxide ion activity. Both of these factors would be expected to result in CO_2/CO ratios smaller than those in our molten carbonate cells, although the anode gas in aluminum electrolysis cells is mainly CO_2. Thonstad[9,10] has postulated electrochemical mechanisms on carbon surfaces to explain the CO_2 production. Because of the importance of the nature of the gas produced for operation of the present cells, studies of the mechanism and methods for optimizing it should be made.

INFLUENCE OF ASH

Ash might be expected to affect the cell by increasing melt viscosity and increase the resistance by introducing impurities that poison the carbon surfaces. Activation polarization could also increase by adding impurities that reduce current efficiency.

In cell III, runs from I to W had 10 wt% fly ash in the electrolyte, but there were no deleterious effects due to the ash. The performance of graphite anodes seemed unaffected by the ash. The charred coal anodes were tested with ash in the electrolyte only; however, their superior performance, compared with graphite, indicated that the ash was not harmful. The container and insulators were not corroded after hundreds

of hours of use in the presence of ash. The only unresolved aspect was the possibility that the iron impurity may have been the cause of the current efficiencies below 100%; however, equally likely was the possibility of mechanical loss of anode gas. That point needs further resolution.

The solubility of ash in the molten carbonate is limited, although unknown at present. The fact that ash constituents seemed to precipitate from the melt suggests that, in a large scale cell, ash might be removed by allowing the melt to become saturated so that additional ash simply falls to the bottom of a cell.

VII EXTENSION OF CONCEPT TO POWER GENERATION

The goal of this program is to increase the efficiency of utilization of the work energy in coal, compared with steam-electric power generation, by direct production of electricity. Although the information required for careful designing is not available, it is instructive to consider, in a preliminary way, overall systems for using the concept in power generation.

Although our results have not defined the exact ratio of CO_2 and CO that would be produced in a large scale cell, the system does produce electricity. A possible flow chart is shown in Figure 14. As shown, the coal would be converted into a usable form for electrodes, and that process would produce gases, the volatile components of coal. The electrodes would be used in the carbon/air fuel cell, and the gases would be used either in other fuel cells (using the hydrogen and hydrocarbons) or as sources of heat. Technology for some of the steps is already part of industrial practice. Carbon monoxide is converted to H_2 by several commercial processes (see Haddeland[11] or Savage[12] or Hottel and Howard[13], and Soderberg electrodes are produced for the aluminum industry (see Mantell).[14]

An alternative concept for the use of coal could avoid the fabrication of electrodes. This approach would use coal of suitable size in a basket-type electrode suspended in the molten carbonate electrolyte. In this system, the coal gases, many of which are electrochemically active, would be consumed directly at the electrode to produce additional power.

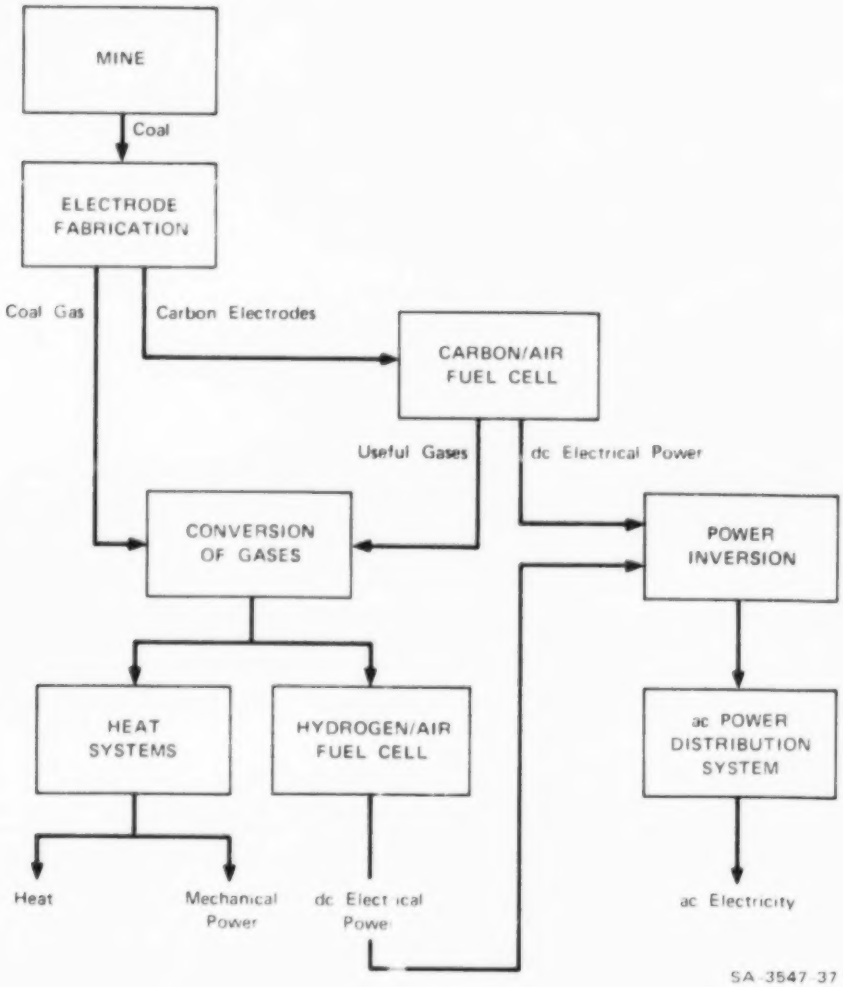

FIGURE 14 FLOWCHART FOR COAL-TO-ELECTRICITY SYSTEM

The electrochemical cell itself will receive much attention in terms of design in future engineering studies. The air cathode must be engineered to be electrochemically compatible, in terms of current density, with the anode area. The hydrostatic pressure of the liquid electrolyte must be accommodated in the operation of porous, gas diffusion, air electrodes. The internal resistance of the electrolyte must be kept low, and ash removal methods must be incorporated into the design.

Whatever the final design of the cell, the anode gases must be collected, and electronic contact to the carbon anode must be made. In the concept envisioned, a conductive and premolded anode is used. The thickness of this anode would be determined by mechanical strength and electrical conductivity requirements. For immediate purposes, an electrode thickness of two to four centimeters is assumed.

The rate at which the electrode must supply carbon is dependent on the area of the cathode and the current density. For a current density of 100 mA/cm^2, the total current will be 20 A/cm length of an electrode immersed to 100 cm. Thus, the electrode must move down into the electrolyte at a rate of about 1 cm/hour, and each 1-meter length of the cell would produce 2000 Amperes.

The current density assumed will influence the cell voltage in two ways: activation and concentration polarization (assumed to be 200 mV from the present results) and resistive loss. An anode to cathode spacing of 1 cm would result in a 50-mV IR drop since the melt resistivity is about 0.5 ohm-cm. The total operating voltage then would be approximately the 1.1 volts observed for charred coals minus 0.25 (or 0.85 volts). From the observed current efficiencies and assuming that only CO_2 is produced, we can expect the efficiency of an operating cell to be at least 80% (however, values close to 100% can probably be attained).

On that basis the cell should produce

$$0.85 \text{ volts} \times 0.80 \times 4 \times \frac{96{,}500 \text{ amp sec}}{3{,}600 \text{ sec/hrs}} = 73 \text{ watt-hours}$$

of electricity per gram atom of carbon. In a conventional steam generator, the efficiency is about 40% of the heat of coal combustion, or about 44 watt-hours of electricity is generated per gram atom of carbon. The efficiency of the fuel cell is significantly greater (1.65 times as great).

Use of the volatile fraction of coal will not be explored in this discussion. The pyrolysis of coal to produce coal char has been studied in some detail[8], and use of the gaseous products is already commercial practice.

The subject of ash buildup and removal will require further investigation. As a means of evaluating the magnitude of the problem, the following calculations can be made. In the cell envisioned above, the electrolyte was 1-cm thick, so there is 1 cm^3/cm^2 of electrode, and for 100 mA/cm^2 about 0.1 cm^3/min of electrode is consumed. In about two days of operation, the melt would contain about 10% ash. If the subsequent ash is insoluble, it is expected that it will precipitate as alkali metal silico-aluminate. The reaction will remove the alkali metal of the carbonate at a rate of about 5% per day. For engineering estimates one can assume that the ash will remove a weight of molten carbonate from the electrolyte about equal to its own weight. The alkali metal from that precipitate can probably be recovered by the same process used in the Kellogg coal gasification concept.[15]

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Appendix A

ANALYTICAL TECHNIQUES, SPECIAL ANALYSES, AND EQUIPMENT

Appendix A

ANALYTICAL TECHNIQUES, SPECIAL ANALYSES, AND EQUIPMENT

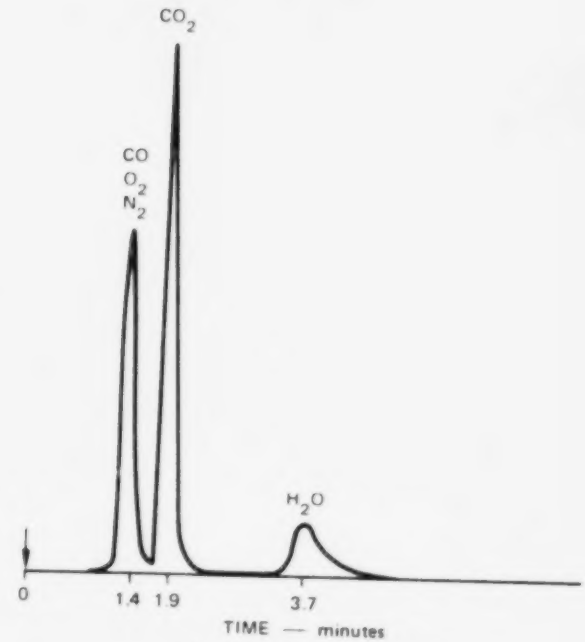
CHROMATOGRAPHIC ANALYSES

The gas chromatograph used was a Loenco Company Model 160 dual-column gas chromatograph. After studies of conditions, the following was established:

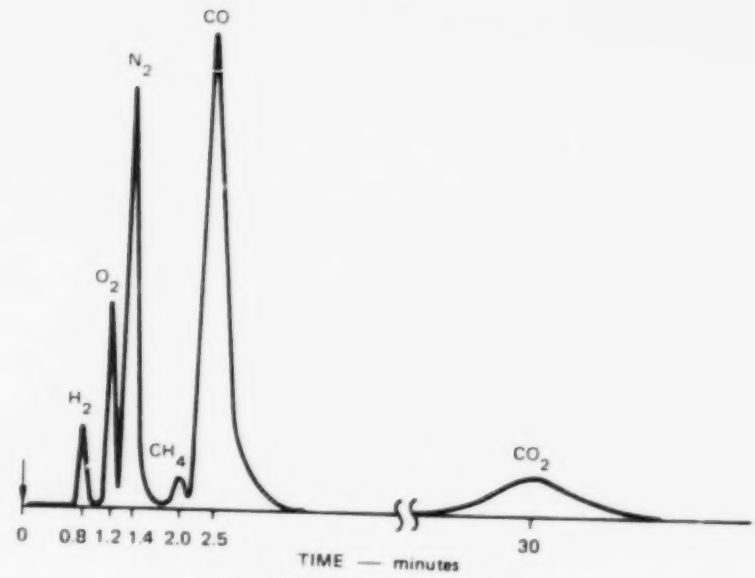
- Column 1: molecular sieve, 0.635-cm o.d. copper tubing, 183-cm long, packed with 5-A 80/100 mesh molecular sieve; carrier flow rate of 65.9 cm^3/min.
- Column 2: Poropak Q, 0.635-cm o.d. copper tubing packed with the Poropak Q material; carrier flow rate of 30.8 cm^3/min.
- Detector: thermal conductivity.
- Detector temperature: 364°K (91°C).
- Column temperature: 403°K (130°C).
- Injection port temperature: 103°K (130°C).
- Carrier gas: helium.

The gases detectable on these columns are indicated in Figure 15. As indicated, the Poropak Q (PPQ) column was used to quantitatively assay CO while the molecular sieve (MS) column was used to assay CO_2.

Typical calibration curves for CO_2 and CO are presented in Figure 16. The curves are presented at attenuation of x 32 (CO) and x 128 (CO_2). That is, the sensitivity for detection of these gases can be increased 32 and 128 times from the ranges normally used during runs. Typical elution times and estimated limits of detection are listed in Table 3.



(a) POROPAK Q COLUMN



(b) MOLECULAR SIEVE COLUMN

SA-3547-38

FIGURE 15 ELUTION OF GASES

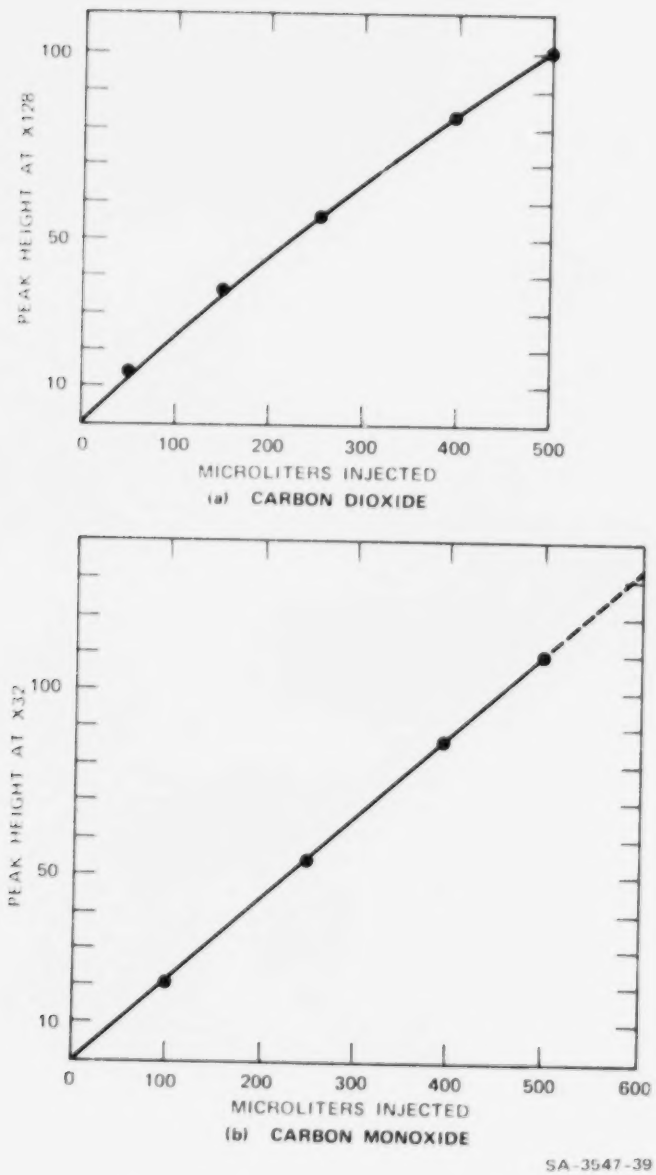


FIGURE 16 CALIBRATION CURVES

Table 3

ELUTION TIMES AND ESTIMATED DETECTION LIMITS FOR VARIOUS GASES

Gas	Porapak Q® Column		Molecular Sieve	
	Elution time min	Estimated detection limit ml/1000 ml	Elution time min	Estimated detection limit ml/1000 ml
Hydrogen	-	-	0.8	10
Oxygen	1.4	-	1.2	0.3
Nitrogen	1.4	-	1.4	0.4
Methane	-	-	2.0	0.05
Carbon Monoxide	1.4	-	2.5	0.5
Carbon Dioxide	1.9	0.15	30	200
Water	3.7	1	-	-

The typical chromatographic procedure was to activate the instrument at the beginning of the day, and, during the next two hours, to then check the flow rate of the carrier gas in each column. During that period, and as free time during the day allowed, injections of a check mix were made to assure constancy of chromatographic response. The elution times and chromatographic response were remarkably constant for all gases during the course of this study with the exception of the behavior for carbon monoxide. The response to this gas varied from day to day by as much as ± 10%, whereas the response for all other gases varied by about 2%. The behavior of CO during a single day, however, was similar to the constancy of the other gases. Since calibration every day served to assure accuracy of analysis within 2% error, no further study of the anomalous behavior of CO was made.

SPECTROGRAPHIC ANALYSIS OF FLY ASH

Fly ash, formed from the combustion of pulverized coal and discharged from an electrostatic precipitator, was used to contaminate the ternary carbonate eutectic. The elemental spectrographic analysis of the ash, made by the American Spectrographic Laboratories, Inc., San Francisco, California, on assay ASL #2151, is given below in weight percent.

Fe	20	Sr	0.02
Al	15	Mn	0.02
Ca	1	Cu	0.01
K	1	Zr	0.03
Mg	0.6	Ni	0.01
B	0.6	Mo	0.01
Ti	0.85	Co	0.005
Na	0.5	Ga	0.005
Li	0.1	Y	0.005
Zn	0.1 (?)	Sc	0.001
Ba	0.06	Be	0.002
Cr	0.02	Pb	<0.005
V	0.02		

Si - nondetectables Balance

PROXIMATE ANALYSES OF COAL SAMPLES

Samples of four types of coal were obtained from Commercial Testing and Engineering Company, Chicago, Illinois. Analyses of these coals, as provided by Commercial Testing and Engineering, are given below.

PEABODY CHAR		
	As received	Dry basis
% Moisture	7.55	--
% Ash	13.01	14.07
% Volatile	8.92	9.65
% Fixed carbon	70.52	76.28
	100.00	100.00
Btu/lb	11,396	12,327
% Sulfur	1.46	1.58

POCAHONTAS		
	As received	Dry basis
% Moisture	2.33	--
% Ash	4.37	4.47
% Volatile	25.42	26.03
% Fixed carbon	67.88	69.50
	100.00	100.00
Btu/lb	14,702	15,053
% Sulfur	0.41	0.42

ILLINOIS NO. 6 SEAM		
	As received	Dry basis
% Moisture	7.07	--
% Ash	8.56	9.21
% Volatile	32.82	35.32
% Fixed carbon	51.55	55.47
	100.00	100.00
Btu/lb	12,342	13,281
% Sulfur	1.81	1.98

DECKER MINE		
	As received	Dry basis
% Moisture	22.51	--
% Ash	5.10	6.97
% Volatile	29.42	37.97
% Fixed carbon	42.67	55.06
	100.00	100.00
Btu/lb	9,513	12,277
% Sulfur	0.34	0.11

LIST OF PRINCIPAL ELECTROCHEMICAL EQUIPMENT

Three dual-channel strip-chart recorders Mosely 2100B

Potentiostat, Princeton Applied Research Corporation, Model 173

Wave-form generator, Princeton Applied Research Corporation, Model 175

x-y Recorder, Hewlett Packard, Model 7035B

Conductivity bridge, Philips Corporation, Model GM 4249

Electrometer, Keithly, Model 610A

Programmable power supply, New Jersey Electric Company, Model SVC 10-5

Oscilloscope, Tektronix, Model 535A

Appendix B

RECORD OF EXPERIMENTS

TABLE I. RECORD OF EXPERIMENTS PERFORMED

Cell	Run	Anode	Ash Present	Temperature K	Temperature °C	Voltage: Anode Versus Reference Open Circuit	Voltage: Anode Versus Reference At 100 mA	Gas Composition During Electrolysis Fraction CO_2	Gas Composition During Electrolysis Fraction CO	Gas Composition During Electrolysis Ratio CO_2:CO	Gas Composition During Electrolysis Fraction CO_2	Gas Composition During Electrolysis Fraction CO	Gas Composition During Electrolysis Ratio CO_2:CO	Electrolysis Current mA	Current Efficiency	Remarks
I	A	Graphite	-	838	563	-0.60	-0.19									Cells I and II were designed for anode voltage studies only. Analyses of anode gases were not made with cells I and II.
	B	Graphite	-	731	458	-0.52	0									
	C	Graphite	-	943	670	-0.74	-0.32									
	D	Graphite	-	1053	780	-1.03	-0.76									
II	A	Graphite	-	656	383	-1.28	-0.80									
	B	Graphite	-	865	592	-1.36	-0.78									
	C	Graphite	-	923	700	-1.41	-0.74									
	D	Graphite	-	1031	758	-1.53	-0.93									
	E	Graphite	-	1031	758	-1.58	-1.10									
	F	Graphite	-	923	700	-1.10	-0.84									
	G	Graphite	-	1001	778	-1.36	-0.88									
	H	Graphite	-	1126	903	-1.53	-1.10									
III	A	Graphite	-	773	500	-0.63	-0.08									
	B	Graphite	-	773	500	-0.92	-0.04	.011			.014			100	122	Runs 2H, A to D. Probable interference in polaro-graphic measurements by electrolytic deposits at cathode.
	C	Graphite	-	1163	890	-1.06	-0.81	.060	.003	.050	.083	.028	3.0	100	1.2	
		Graphite	-	1163	890						.080	.266	.019	200	1.1	
	D	Graphite	-	881	608	-1.31	-0.15				.006			100	3	
	E	Graphite	-	871	598	-1.01	-0.1	.080			.272			100	92	Runs III E to N inclusive. Reference electrode erratic.
	F	Graphite	-	973	700	-0.13	-0.08	.009			.240			100	92	
	G	Graphite	-	1078	805	-0.92	-0.37	.027	.009	3.0	.240	.028	8.81	100	92.0	
		Graphite	-	1078	805						.06	.024	2.33	20	98.2	
	H	Graphite	-	1183	910	-0.26		.017	.114	.150	.038	.275	.2041	100	92.8	
		Graphite	-	1183	910						.032	.232	.142	30	88.1	
	I	Graphite		293	320	-0.81	-0.3	.003			.218			100	100	Water add to electrolyte at Run III-I.
	J	Graphite		973	700	-0.65	-0.05	.023	.004	5.75	.230			100	81.6	
	K	Graphite		1168	895	-0.42		.109	.107	.268	.170	.180	.234	100	104	
		Graphite		1168	895						.102	.530	.2684	200	74.9	
	L	Graphite		983	710	-	-	.006	.003	2.00	.021	.001	21.0	100	5.0	Probable leak in system.
	M	Graphite		981	708	-1.07	-0.85 to -0.55	.031	.006	5.17	.136	.003	39.2	100	62.2	
	N	Graphite		973	700	-0.71	-0.28 to -0.38	.017	.002	8.50	.233	.003	71.3	100	70.3	
	O	Graphite		1169	896	-0.80	-0.9	.090	.127	.183	.091	.182	.193	100	83.3	Standard procedure factored as of Run III-O.
		Graphite		1169	896		-0.65				.086	.503	.171	300	2.0	
	P	Peabody**		827	681	-1.10	-1.10	.005			.102			100	88.9	Leak discovered in system.
	Q	Peabody**		832	560	-0.96	Too erratic	.010			.223			100	72.2	
	R	Peabody**		1090	770	-1.08	-0.91	.188	.102	1.63	.174	.292	.841	100	53.0	
	S	Peabody		971	698	-1.12	-0.9	.172	.006	12.0	.253	.016	11.6	100	58.0	
	T	Peabody**		982	709	-1.08	-0.79	.021	.001	>20	.161	.002	5.30	100	38.4	
		Peabody*		982	709		-0.52				.254	.024	9.53	200	21.4	
	U	Pocahontas		98	712	-1.10	-1.10	.061	.030	2.03	.192	.028	2.36	100	67.0	
		Pocahontas		98	712		-0.74				.410	.049	9.08	200	82.8	
	V	Illinois**		924	701	-1.13	-1.13	.042	.032	1.14	.183	.082	2.23	100	20.6	
	W	Illinois**		973	700	-1.09	-0.13 to -0.43	.073	.010	7.3	.131	.018	9.19	200	22.0	

* Values were less than 0.001

** Peabody char.

*** Illinois No. 6 seam.